CHAPTER 5

Implications of Soil Tillage for Crop and Weed Seeds

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CONTENTS

5.1 INTRODUCTION

In arable fields, soil cultivation is carried out for a number of reasons, and influencing the fate of seeds is one of its most important objectives. It has been evident to farmers for a long time that germination and emergence of seeds can be enhanced by cultivating the soil before sowing. Soil cultivation removes the previous vegetation and hence enhances the competitive situation for the crop. It also facilitates sowing of seeds into the soil. Moisture conditions tend to be more favorable within the soil than on the soil surface. The probability of seeds being removed by birds or other animals is less for seeds that are incorporated into the soil than for seeds that lie on the soil surface.

In traditional systems, tillage operations are comprised of a sequence of cultivation operations, all of which affect seeds. In temperate regions, the following scheme is relatively common. Shortly after harvest, shallow stubble tillage is carried out to promote germination of shed crop and weed seeds by incorporating them into the upper layer. Stubble tillage can be repeated once or twice, thereby killing newly emerged seedlings and promoting additional germination. Stubble tillage is usually followed by primary tillage, and in traditional systems this consists of plowing to a 20- to 30-cm depth. Plowing inverts the layers and mixes the soil, so it affects the position of seeds drastically. Primary tillage is followed by one or more seedbed preparations, which are performed to level off the soil surface, to recompact the very loose horizon beneath the sowing horizon, and to create a seedbed with fine aggregates in the upper centimeters. Finally, sowing is accomplished, and this again results in some weed seed movement within the affected layer.

These systems have been followed more or less closely over the past decades. However, with tractors becoming more powerful and the increasing working widths of agricultural machinery there has been a tendency for a general increase in both cultivation depths and intensity that has resulted in negative impacts on the environement, in particular with respect to soil compaction and erosion. Some of these problems can be overcome by using noninversion or no-tillage systems that have been developed in the United States and in Europe during the second half of the 20th century. These systems affect weed and crop seeds very differently and as a result have a significant impact on crop establishment and the population dynamics of weeds and volunteer crops.

A large number of reviews and books have been written on the implication of environmental factors on the dormancy and germination of seeds, and these cover environmental factors affecting seeds while on the plant, in a seed store, or in the soil.[1–5] A wide range of papers have dealt with the effects of tillage on crop growth and weeds.[6–11] A number of papers have been published on the implication of tillage for seedbanks and seedling emergence.[12–14] In this chapter, an attempt is made to review the potential impacts of soil cultivation on all aspects of seeds. Both crop and weed seeds are subjects of the review, which covers the implications of tillage for crop establishment as well as the implication of tillage for the persistence of crop and weed seeds within the soil, their emergence, and, finally, the consequences for a crop-production system.

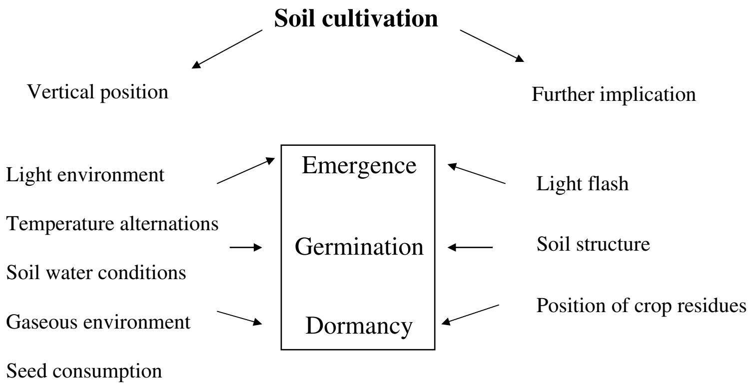

Figure 5.1 The implication of soil cultivation for seed dormancy, germination, and emergence. Left side: the implication of vertical position for the seeds' environment. Right side: further implications of soil cultivation that are not directly related to burial depth.

The first part of the chapter analyzes the effects of tillage, beginning with the effects of soil cultivation on vertical distribution of seeds (Figure 5.1 left) and explaining further implications of tillage for seeds (Figure 5.1 right). The vertical position affects the light environment, hydrothermal regime, gaseous environment, and the probability that seeds will be removed by birds, rodents, or other seed-eating animals in the field. During soil cultivation, seeds may receive a light flash and other sudden changes in environmental conditions that may stimulate germination. Soil cultivations affect soil structure and the position of crop residues, thereby affecting the physical and chemical environment of seeds. In this analytical part of the chapter, the results of short-term experiments as well as laboratory and model experiments are cited; long-term effects of tillage are the subject of the next part. The implications of cultivation regimes are discussed within a comprehensive farming system context, taking the results of long-term field experiments as examples. In the final section, conclusions are drawn for the implications of tillage for sustainable crop-production systems.

5.2 THE EFFECT OF SOIL TILLAGE ON THE VERTICAL DISTRIBUTION OF SEEDS

Soil tillage disturbs the soil, and as a result seeds are transferred from one layer to another. A number of studies have been carried out to examine the effect of soil tillage on the vertical distribution of seeds. In some experiments, glass or plastic beads have been used to simulate weed seeds. Using beads with various colors enables the experimenter to follow the fate of seeds placed originally at various predefined depths. Data on the effects of single cultivations can then be used to calculate the effect of repeated cultivations.[15–18] Moss[18] conducted experiments using beads together with seeds of three grasses (*Alopecurus myosuroides*, *Bromus sterilis*, and *Avena fatua*) and of *Galium aparine*. In model experiments, he studied the effect

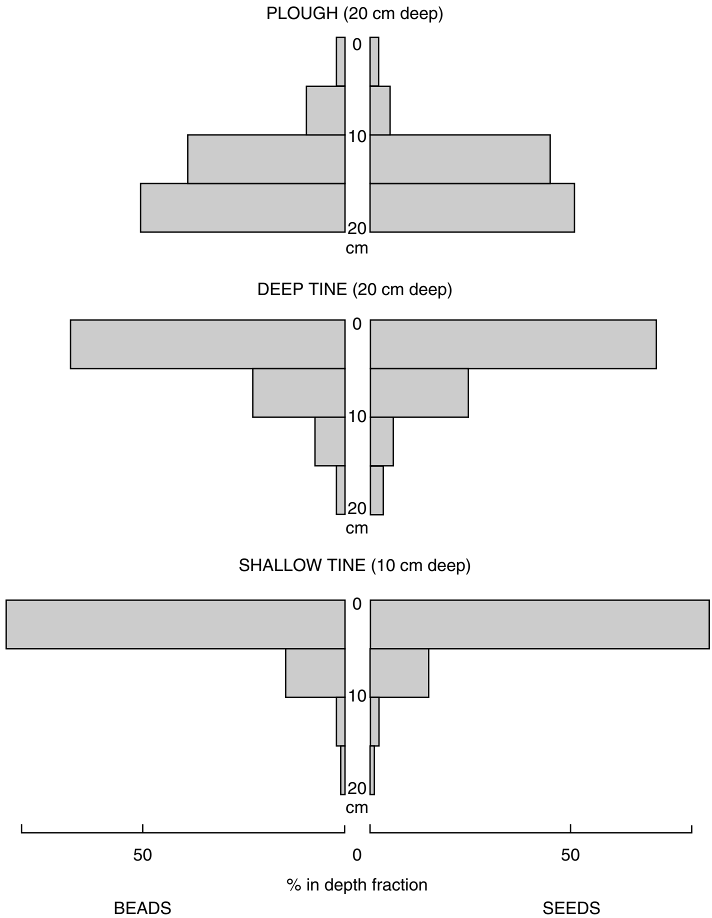

Figure 5.2 Effect of soil cultivation on vertical distribution of seeds (mean of four species) and plastic beads. Plowing at 20 cm depth, tine cultivation at 20 cm respective 10 cm depth. Tine cultivation was repeated once. All plots were cultivated with a spring tine cultivator at 5 cm depth to level the surface after primary tillage. Experiment on a sandy loam near Oxford. (From Moss 1988, with permission.)

of ploughing (20 cm), deep tine cultivation (20 cm), and shallow tine cultivation (10 cm). Seeds and beads reacted similarly (Figure 5.2). Plowing resulted in inverting the seeds and beads upside down. Both types of tine cultivation resulted in merely mixing the seeds into the upper soil layers. The use of 20-cm tine cultivation resulted in slightly deeper distribution of seeds than 10-cm tine cultivation.

Field experiments involving natural seed dispersal basically support these observations.[19,20] In a long-term study at Lautenbach, in southwest Germany, integrated farming was compared with conventional farming over a period of 17 years. In this study, an integrated package of husbandry techniques (integrated farming system = IFS) was compared to conventional farming (conventional farming system = CFS). In IFS, noninversion tillage was used at a depth of around 25 cm. In CFS, annual

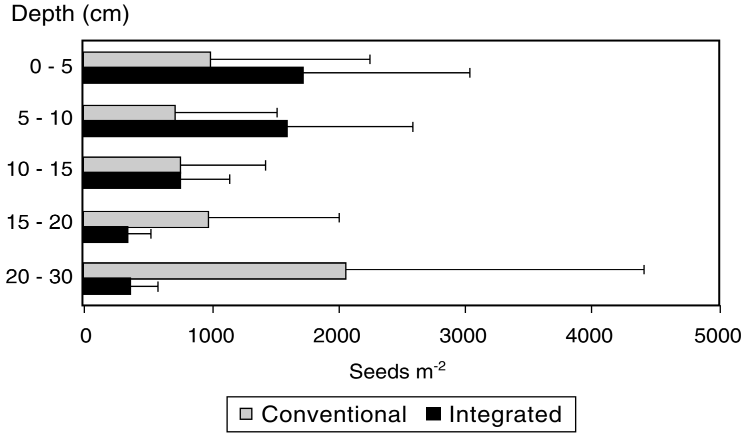

Figure 5.3 Vertical distribution of a weed seedbank (seeds m^{-2}) in an experiment at Lautenbach in southwest Germany after 17 years of experimentation. In integrated farming, primary tillage consisted of noninversion tillage at around 25 cm; in conventional farming, it consisted of annual plowing at around 30 cm depth. Data are means of three field experiments, error bars represent 1 standard deviation.

plowing at around 30 cm was implemented. The vertical distribution of seeds was very much affected by the tillage regime (Figure 5.3). Whereas in IFS the majority of seeds was accumulated within the upper 10 cm, a different distribution was assessed in CFS plots, with a relatively homogenous distribution of seeds within the upper layers and a relatively large number of seeds within the 20- to 30-cm-depth layer.

Sometimes, the vertical distribution of seeds differs significantly from the expected distribution. In an experiment near Vienna, Austria, enormous numbers of seeds were found in the layer 10–20 cm deep in no-tillage plots.[21] The most likely explanation for this was that seeds had been washed into cracks after heavy rainfall. In such soils, with a high clay content, cracks regularly develop during dry weather periods. A similar explanation was assumed in a study by Moss,[22] who observed large seed losses from the soil surface between July and October in an experiment in England. Apart from tillage implements, soil-burrowing animals can also significantly alter the vertical distribution of seeds within the soil profile. Not only have rodents been reported to affect seed distribution but also earthworms.[23–24]

5.3 THE IMPLICATION OF THE VERTICAL POSITION OF SEEDS

The vertical position of seeds decisively affects the probability of their successful emergence.[25–27] In addition, it also affects the seeds' environment and in this way seed dormancy, germination, and the probability of seed predation and seed decay. Seeds of many weed species have developed mechanisms to monitor their vertical position in soils and hence to distinguish between shallow and deep burial. Generally, factors indicating shallow burial, or a position on the soil surface, such as light,

alternating temperatures, decreasing soil water contents, etc., promote germination. Environmental conditions resulting in deep burial tend to deepen dormancy and therefore reduce the probability of germination. In the following chapters, the vertical distribution of the environmental factors is described and the implication of these factors for seed dormancy, germination, and seed predation assessed.

5.3.1 Effects of the Light Environment

Tester and Morris[28] reviewed the literature on light penetration into soil. Most measurements showed that light rarely penetrates deeper than 4–5 mm into the soil. Hence, light is an ideal parameter to indicate a shallow burial depth within the soil.

Light can affect seed germination and dormancy in various ways, and there is an abundant literature on this subject. Here, only the major types of reactions that are relevant for crop and weed germination in the context of tillage are explained and demonstrated. Light can promote seed germination, inhibit germination, deepen dormancy, alleviate dormancy, or have no apparent effect on seeds. The effect of light on seeds depends on the species, the physiological status of the seed, and on the quality and quantity of light.

Among weeds, light sensitivity, or a requirement of light for germination, is very common. Frankland argued that light sensitivity is one reason why particular species are weeds.[29] Light sensitivity is a physiological status of seeds that they can aquire on the mother plant or while exposed to darkness or to far-red-spectrum light.[30] This restricts seed germination to the upper few mm of the soil and thereby prevents seeds from germinating when too deep in the soil, where germination would not result in successful emergence. An example is shown in Table 5.1. Light-sensitive

Table 5.1 Germination of Light-Sensitive Lettuce Seeds

Exposure Time (min)	Planting Depth (mm)	Germination (%)
6	surface	68
	2	1
	2 (darkened)	0
	6	5
60	surface	63
	2	24
	2 (darkened)	1
	6	2
600	surface	71
	2	77
	2 (darkened)	1
	6	7

As a function of depth in broomfield sand after various exposures to light. Darkened treatments were covered by four layers of aluminium foil to keep seeds in absolute darkness.

Source: From Woolley and Stoller, 1978, with permission.

lettuce seeds were sown into cups filled with Broomfield sand, either on the soil surface, 2 mm deep into sand, or 6 mm deep. Cups with a 2-mm sowing depth were covered with four layers of aluminum foil or left uncovered to study the implication of light on germination. The highest germination rates were recorded in treatments where the seeds were sown on the soil surface. The 2-mm depth resulted in reduced seed germination, in particular when cups were exposed to light for only a short period of time.

The physiological basis for the reactions of seeds to light has been studied extensively and is rather complex. For further reading consult, e.g., Casal and Sánchez.[31] For a basic understanding of seed responses to light, it is useful to follow certain principles. Promotion and inhibition of seed germination by light is mediated by phytochromes, a small family of photoreceptors. Phytochromes can shift between two interconvertible forms: Pfr, the active form of phytochromes (= far-red-light-absorbing form of phytochromes), and Pr, the inactive form of phytochrome (= red-light-absorbing form of phytochromes). Red light causes Pr to change into Pfr, hence promoting seed germination; far-red spectrum light results in the opposite process, thereby deepening dormancy. Borthwick et al. demonstrated the interconvertible nature of phytochromes in germination tests with light-sensitive *Lactuca sativa* seeds (Table 5.2).[32] When lettuce seeds were exposed to red light for 1 min, they germinated at high rates. When they were transferred to far red light for 4 min, they had much lower germination rates. Repeated cycles of irradiation with red or far red light showed that this reaction was reversible. In nature, the relation of red light to far red light indicates solar radiation or radiation filtered through a leaf canopy. Sunlight consists of a larger proportion of red light than far red light. Sunlight filtered through a leaf canopy has a higher proportion of far red light than red light and so prevents seeds from germinating beneath a leaf canopy.[33–35] In soil, light-sensitive seeds cannot germinate unless they receive a germination-triggering light stimulus. In darkness, a

Table 5.2 Photoreversal of Promotion and Inhibition of Germination of Light-Sensitive Lettuce Seeds

Irradiation	Germination (%) at 20°C after Irradiation Treatments at 26°C	6–8°C
R	70	72
R-FR	6	13
R-FR-R	74	74
R-FR-R-FR	6	8
R-FR-R-FR-R	76	75
R-FR-R-FR-R-FR	7	11
R-FR-R-FR-R-FR-R	81	77
R-FR-R-FR-R-FR-R-FR	7	12

CV. Grand Rapids at 20°C after irradiation at 26°C and 6–8°C. Seeds were irradiated with alternating red and far red light and hereafter tested in a germination test in darkness. R = 1 min red light, FR = 4 min far red light.

Source: From Borthwick et al., 1954, with permission.

process called *dark thermal reversion of Pfr* can take place; this process results in a gradual increase of Pr within the seed and hence in the induction of light sensitivity.

On the other hand, white light can inhibit germination of seeds, particularly that of light requiring seeds. This is the case at very high irradiation intensities.[36–37] Under natural conditions a situation with high irradiance will very often coincide with high temperatures and a fast drying of the upper soil layers. Hence, prevention of germination by high-irradiance light may be another mechanism to prevent germination under conditions where successful seedling establishment is unlikely. Benech-Arnold et al., however, claims that the high-irradiance reaction is not yet studied sufficiently to explain its adaptive significance.[5]

Apart from the types of reaction described here, there exists a wide range of other reactions or combinations of reactions to light. A small number of species require darkness for germination, e.g., *Phacelia tanacetifolia* as a relatively well-known example. For further reading see Baskin and Baskin.[4] Also, seeds respond to their environment, and so their responses change with time. Botto et al., for instance, showed that the germination of *Datura ferox* seeds in response to red light, far red light, and darkness was affected by burial depth and covering vegetation.[38] It has been shown that for many weed species the level of light sensitivity of seeds varies with season.[39–41]

The germination of most crop seeds seems to be unaffected by light. Crop production and related selection of genotypes that can germinate in high proportions shortly after harvest resulted in a gradual loss of dormancy. However, there are exceptions. Oilseed rape, for instance, is known as a crop whose seeds are unaffected by light.[42] Nevertheless, they sometimes can be highly sensitive to light, as shown by Schlink when exhumating oilseed rape seeds that had been buried in soil for several months or even several years.[43] The exhumation of seeds at night using a torch with a green safety light for orientation showed that oilseed rape seeds can acquire light sensitivity in soil. Light sensitivity can also be induced artificially.[44] When oilseed rape seeds are exposed to darkness and suboptimal germination conditions, seeds develop a requirement for light for several weeks. When given light during the imbibition treatment, the proportion of seeds not germinating in darkness thereafter is reduced. The effects of various combinations of light and darkness over a 4-week imbibition treatment are summarized in Table 5.3. When seeds were exposed to darkness for a

Table 5.3 Effect of Time in Light and Darkness During a 4-week Period of Water Stress

Weeks in Light	**0**	**1**	**2**	**3**	**4**
Weeks in Darkness	**4**	**3**	**2**	**1**	**0**
Apex	–0.259	–0.695	–1.435	–1.691	–1.919
	(37.2)	(24.8)	(7.6)	(3.2)	(1.6)
Bristol	0.006	–0.227	–1.092	–1.777	–1.866
	(50.0)	(39.2)	(14.0)	(2.8)	(2.0)
s.e. = 0.2177 (d.f. 40)					

(–1.5 MPa) on subsequent exhibition of dormancy in oilseed rape when testing seeds in a germination test in darkness. Oilseed rape cultivars apex, bristol; percent dormant seeds in darkness as logit transformed means with corresponding original values, in parentheses.

Source: From Pekrun et al., 1998, with permission.

Table 5.4 Stimulation of Germination by Fluctuating Temperatures in a Range of Species Originating from Five Different Habitat Types

Habitat	No. of Species Examined	% Stimulated by Fluctuating Temperatures
wetland	66	42
Disturbed ground	61	18
grassland	99	2
woodland	20	5
remainder	43	0

Seeds were given light during the germination test.

Source: From Thompson and Grime, 1983, with permission.

4-week imbibition period, large proportions of the seeds acquired light sensitivity and so were unable to germinate in a germination test in darkness. In contrast, when seeds were exposed to light for 2 weeks and then to darkness for another 2 weeks, the proportion of seeds remaining ungerminated in a germination test in darkness was much smaller. Almost no seeds acquired light sensitivity when seeds were exposed fully to light during a 4-week incubation period in an osmotic solution. Hence, the light environment can substantially affect not only weed seeds but also crop seeds.

5.3.2 Effects of Temperature Regimes

The germination of seeds after shallow burial can be promoted not only by light but also by alternating temperatures. Alternating temperatures are a response to shallow burial and the absence of a leaf canopy or other material covering the soil, e.g., plant residues. Hence, they indicate a situation with a high probability of successful emergence.

Seeds of many plant species are able to respond to the amplitude of temperature alternations. Quite often, light is needed additionally to initiate germination but also enhances the reaction of seeds to temperature alternations.[45–47] Table 5.4 shows the results of screening plant seed species of various habitats. Among the species of seeds that originate from wetlands and disturbed habitats, such as arable fields, the promotion of germination by temperature alternations is relatively common. It can also be observed for oilseed rape seeds.[48] Seeds of six cultivars of oilseed rape were imbibed in darkness and suboptimal germination conditions to induce dormancy (Table 5.5). Subsequently, the seeds were tested in a germination test in darkness under three temperature regimes. Germination was clearly enhanced by alternating temperatures of 20/10°C, resulting in smaller proportions of dormant seeds than when testing germination at 18/12°C or a constant 15°C. Hence, the temperature regime apart from light is also an indicator of shallow burial and therefore promotes germination of seeds from a range of species.

5.3.3 Effects of Soil Water Conditions

Soil water conditions vary enormously within the soil. They depend very much on actual and preceding weather conditions and on soil type. In areas with a temperate climate, the soil is usually saturated early in the year. At that time hardly any moisture

Table 5.5 Effect of Temperature Regime During Germination Test

Temperature (°C)	Apex	Bristol	Envol	Falcon	Libravo	Starlight
15	0.533	0.686	0.100	–1.178	–0.624	0.757
	(74.8)	(79.6)	(54.8)	(8.0)	(22.4)	(82.4)
18/12	0.157	–0.091	–0.140	–1.860	–0.780	0.357
	(57.2)	(50.8)	(43.2)	(1.6)	(16.8)	(32.8)
20/10	–0.390	–0.254	–0.628	–2.308	–1.270	–0.793
	(32.4)	(38.0)	(23.2)	(0)	(7.2)	(16.8)
s.e. = 0.1290 (d.f. 72)						

Alternating temperatures at a 12-h/12-h rhythm on exhibition of dormancy of oilseed rape after 4 weeks imbibition under conditions of water stress (–1.5 Mpa) and darkness at 20°C. Percent dormant seeds in darkness as logit transformed means with corresponding original values, in parentheses.

Source: From Pekrun et al., 1998, with permission.

gradient is measurable within the arable layers of the soil. The same applies to situations after longer periods of heavy rainfall. However, after a period with dry weather conditions following a period with evaporation losses larger than rainfall, a gradient develops with drier soil in the upper soil layers and moister soil in the deeper layers.

As a result, germination conditions tend to be more favorable within the soil than on the soil surface, not only due to the moisture gradient but also due to an increased seed soil contact area for seeds lying within the soil and in close contact with surrounding soil aggregates.[49] The optimum sowing depths for agricultural crops are very much a function of this relationship. The ideal sowing depth provides adequate water for the seed to imbibe and germinate, under a wide range of soil water conditions, and at the same time ensures high emergence rates. Naturally, this is a function of seed species and soil conditions, in particular of seed size, seedling morphology, soil type, and size of soil aggregates.

Imbibition of seeds is absolutely essential for germination and hence an adequate water potential of the soil.[50,51] Table 5.6 shows water potentials that resulted in a 50% reduction of germination in a number of crop species. Germination was reduced by 50% at water potentials between –5 bars and –14 bars, which are water potentials that are regularly measured under field conditions.

Apart from influencing germination directly, soil water conditions also can affect the ability of seeds to react to other environmental factors as well as the seeds' dormancy status. Experiments by Berrie et al. testing the germination of light-sensitive lettuce seeds showed that at seed moisture content of 6% seeds were not able to react to red light (Table 5.7).[52] However, when seeds were adjusted to increasing moisture content, the responsive ability of seeds to light increased. The opposite process was observed when seeds were dried gradually. Similarly, induction of light sensitivity in nondormant oilseed rape seeds took place only when seeds were held at a particular hydration status for a longer period of time.[44] In dry seeds, induction of light sensitivity was not possible.

Seed dormancy can be increased or alleviated by soil water conditions. Generally, soil water conditions indicating a position on or close to the soil surface tend to alleviate seed dormancy, whereas soil water conditions indicating a position deep down in the profile tend to deepen or maintain dormancy. However, there is a whole

Table 5.6 Maximum Germination, Water Potentials, and their Standard Errors (in Parentheses)

	Maximum Germination (%)	G_{50}(bar)	R_{50}(bar)
Chenopodiaceae			
Beta vulgaris L.	78	–6,3 (1,47)	–17,8 (1,47)
Spinacia oleracea L.	82	–10,6 (0,31)	–(13,6)(0,56)
Compositae			
Cichorium intybus L.	82	–6,7 (0,33)	–9,0 (0,78)
Lactuca sativa L.	100	–7,2 (0,22)	–14,9 (0,42)
Cruciferae			
Brassica rapa L.	99	–10,1 (0,29)	–15,7 (0,63)
Raphanus sativus L.	100	–14,0 (0,35)	–20,2 (1,01)
Cucurbitaceae			
Cucumus sativus L.	96	–8,8 (0,23)	–9,6 (0,45)
Liliaceae			
Allium cepa L.	87	–7,9 (0,26)	–11,2 (0,49)
A. porrum L.	90	–5,7 (0,27)	–9,5 (0,44)
Solanaceae			
Capsicum annuum L.	95	–10,2 (0,22)	–12,2 (0,38)
Solanum lycopersicum L.	98	–6,3 (0,21)	–11,2 (0,42)
Umbelliferae			
Daucus carota L.	84	–8,1 (0,23)	–8,7 (0,49)
Pastinaca sativa L.	91	–4,5 (0,27)	–10,7 (0,54)

Germination was reduced by 50% (G_{50}) and water potentials that reduced the number of seedlings with growing radicles by 50% (R_{50}).

Source: From Ross and Hegarty, 1979, with permission.

range of different types of reaction. For further reading see Hegarty[53] or Baskin and Baskin.[4] For many seed species it has been shown that dehydration results in an alleviation of dormancy.[54,55] Hence, seeds lying on the soil surface during dry weather conditions or seeds lying in a seed store often lose dormancy. This so-called after-ripening process has long been known as a treatment to alleviate dormancy in seeds that are highly dormant at the time of maturation and is recommended as one dormancy terminating treatment by the International Seed Testing Association.[42] Like temperature alternations, alternate wetting and drying can also alleviate dormancy.[4]

5.3.4 Effects of the Gaseous Environment

The soil atmosphere varies with time and depth in soil. Immediately after soil cultivations the gaseous environment equates to atmospheric conditions. However, after a longer period of time a gradient develops from the soil surface with decreased oxygen concentrations and increased concentrations of CO_2 and other gases in deeper soil layers.[56,57] Whether and how fast such a gradient develops depends on a number of factors, in particular the soil water conditions, texture, aggregate size, proportion of continuous macropores, respirative activity of soil life, roots, etc. Figure 5.4 presents measurements of CO_2 in a profile 0–50 cm deep taken over a period of 18 months under a wheat crop in a Mexican loam soil in Columbia, USA.[58] In the deeper soil layers CO_2 content increased during summer and at times of high

Table 5.7 Percentage Germination of Lettuce Seed at 30°C after Irradiation at Low Moisture Content and Following Desiccation.

Estimated Content (%)	Water	Irradiation	Germination (%)	Irradiation	Germination (%)
6.61	↑	red	5.95	red + far red	4.1
8.78	↑	red	22.80	red + far red	5.8
10.54	↑	red	34.25	red + far red	5.6
13.55	↑	red	49.65	red + far red	4.1
15.76	↑	red	66.25	red + far red	6.1
17.32	↑	red	59.00	–	–
17.96	↑	red	69.70	–	–
19.50	↑	red	69.65	–	–
20.26	↑	red	73.00	–	–
20.92	↑	red	80.50	–	–
19.2	↓	red	43.25	red + far red	4.50
16.3	↓	red	41.25	red + far red	6.35
14.2	↓	red	32.25	red + far red	8.00
12.5	↓	red	23.25	red + far red	2.00
11.3	↓	red	22.50	red + far red	9.75
10.3	↓	red	13.25	red + far red	4.00
9.5	↓	red	21.50	red + far red	5.00
7.3	↓	red	14.00	red + far red	3.75
6.8	↓	red	14.25	red + far red	5.50
6.6	↓	red	5.25	red + far red	5.25

Irridiated during moistening (↑) or desiccation (↓). Red dose = 28.5 mJ; far red dose = 103.2 mJ. (↑) estimate for replicate samples; (↓) estimate by interpolation. No light treatment: 7.08 ± 0.33% germination – : not tested.

Source: From Berrie et al., 1974, with permission.

temperature and intensive decomposition of plant residues. They decreased again during the winter.

The gaseous soil environment can have a significant effect on the dormancy and germination of seeds. Here, only a small number of observations are presented that demonstrate the variety of effects that occur. For further reading see Corbineau and Côme.[59] One of the classical experiments on the implication of gases in seed germination was by Wesson and Wareing.[30] They showed that flushing the soil with N_2 significantly enhanced the germination of weed seeds within plastic pots. They assumed that by flushing the soil, seed-produced volatile germination inhibitors were removed. Later, Holm identified these gases as acetaldehyde, ethanol, and acetone.[60]

A number of other gases have been reported to affect the dormancy of seeds. In many species, ethylene has been shown to trigger seed germination. Anoxia, or an atmosphere free of oxygen, also can have seed-dormancy-relieving effects. Corbineau and Côme tested the effects of 3 weeks of anoxia on the dormancy of sunflower seeds.[59] Seeds in air germinated at significantly lower rates than seeds that had been exposed to anoxia for 3 weeks before being transferred to atmospheric conditions. Hence, although oxygen is necessary for germination, anoxia can be important for seeds to increase germination success. On the other hand, an atmosphere poor in oxygen can result in an induction of dormancy. Pekrun et al.[44] showed that imbibing nondormant oilseed rape seeds in pure water in an atmosphere containing 3% O_2

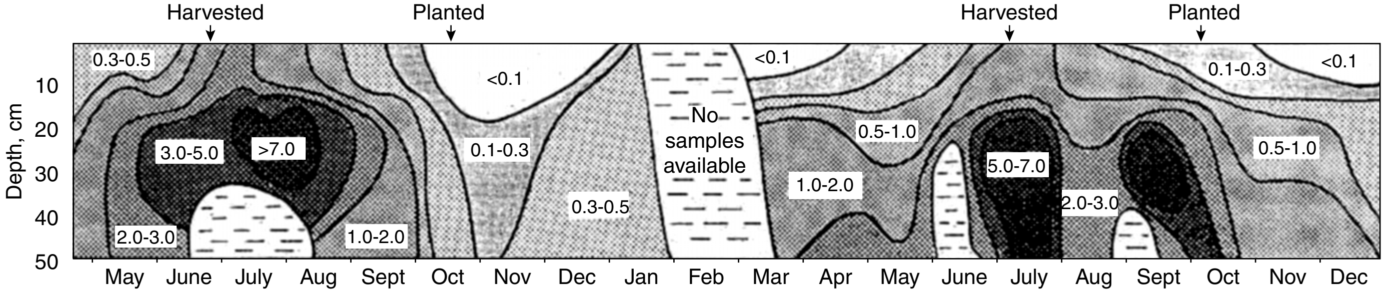

Figure 5.4 Chronoisoplethic graph showing percentage CO_2 at various profile depths under winter wheat in an experiment on a loam soil in Columbia, USA measured during a period of 18 months. (From Buyanovsky and Wagner, 1983, with permission.)

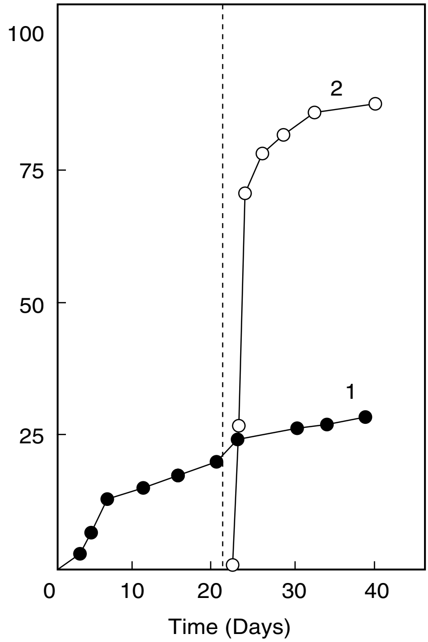

Figure 5.5 Effect of a 3-week treatment in anoxia on germination of dormant sunflower seeds at 15°C placed continuously in air (1), or transferred to air after 3 weeks in pure nitrogen (2). (From Corbineau and Côme, 1995, with permission.)

and 97% N_2 for 2 weeks and maintaining seeds in complete darkness during that time resulted in an induction of dormancy in some of the seeds. Hence, the effects of the soil gaseous environment on seeds is very diverse. Presumably, not all aspects have been studied yet, and there remains a large amount of work in describing the full implications of the gaseous environment on seeds.

5.3.5 Effects of Seed Predation

Seed consumption by animals can have a significant effect on the population dynamics of a range of plant species.[61] Relatively little information is available on the importance of seed predation in arable fields[62–64] and even less on the impact of soil tillage on seed predation. For example, foraging of the harvester ant (*Veromessor pergandei* Mayr.) is reported to be highly selective, with measurable impacts on the survival rates of its host plants.[65] In spring *Malvastrum, Mentzelia*, and *Oenothera clavaeformis* build up the main diet, whereas *Plantago* spp. seeds comprise up to 86% of the seeds collected during the rest of the year.[66] Carabid beetles of the genus *Amara* spp. were shown to exert considerable preferences for seeds of some weed species of arable fields (see Chapter 11). *Amara similata* was selected to elucidate the relative roles of seeds and insects as food sources. Three experiments were done to rank different weed seeds and insects in terms of food value: fecundity in relation to adult diet, larval survival in relation to diet, and larval survival in relation to

Table 5.8 Mean Percentage of Seeds Removed by Seed Feeders Over a 5-Week Period

Week	Tillage Treatment	Mean Percent Consumed Per Week	Mean Percent Consumed Total
1	No-tillage	7.96*	7.96*
	Conventional tillage	2.22	2.22
2	No-tillage	18.92**	26.88**
	Conventional tillage	6.72	8.94
3	No-tillage	14.33**	41.21**
	Conventional tillage	5.76	14.70
4	No-tillage	13.47**	54.68**
	Conventional tillage	6.55	21.25
5	No-tillage	13.85**	68.53**
	Conventional tillage	5.70	26.95

(October 1–November 7, 1986) in no-tillage (NT) and conventional tillage (CT) soybean systems in an experiment in North Carolina, USA. *$p < 0.01$; **$p < 0.001$ for comparison between no-tillage and conventional tillage.

Source: From Brust and House, 1988, with permission.

parental diet. Seeds were found to be of high feed value and insects of low feed value both for adults and larvae.[67] The larvae of harpaline carabids (*Ophonus* spp.) feed almost exclusively upon plant seeds.[68] The carabid beetle *Harpalus rufipes* was studied with respect to its food preference and food quality. Three laboratory experiments were done to clarify the role of weed seeds and insects as food for *H. rufipes*. Seeds of *Taraxacum sp*. were their preferred seed source.[69] However, edaphic seed feeders are unlikely to maintain a close relationship to single-seed species (monophagy). Such a high level of specialization would result in destroying the food resource of the predator and consequently its extinction. However, it can generally be assumed that seeds lying on the soil surface are removed at higher rates by arthropods, rodents, birds, and a number of other animals than those that are incorporated into the soil. In fact, preventing seed consumption is one major reason for sowing crop seeds into the soil instead of broadcasting them onto the soil surface.

Brust and House studied seed consumption by predators in an experiment in North Carolina, USA, where two tillage systems had been established 3 years earlier (Table 5.8).[70] Tillage regimes were comprised of no-tillage and conventional tillage using chisel and disk plowing. No insecticides had been used on either of the treatments for the previous 3 years. Herbicide applications were used at one fourth to one half of the rates recommended by the extension services. Seed consumption was examined for four weed species and wheat over a 5-week period in October and November 1986. Seeds were held in place on cardboard cards with two-sided tape that allowed animals to remove the seeds but that prevented seeds from rolling around. Results show that seed consumption was two to three times higher in no-tillage plots than in plots with conventional tillage. Carabid feeding had the greatest impact, followed by that of ants, field mice, and crickets.

There are a number of observations that support these data. Mittelbach and Gross studied seed consumption by predators in an old field that had been abandoned from agricultural usage 10 years before.[71] Tillage significantly decreased seed consumption by ants and rodents. Also, Kollmann and Bassin, studying seed predation in

wildflower strips, showed that tillage reduced seed predation by animals.[72] Generally, soil-dwelling invertebrates, such as earthworms, mice, slugs, arthropods, spiders, etc., are more abundant in reduced-tilled or no-till fields than in intensively-cultivated soils,[73,74] and so one would expect higher seed predation rates in these fields. A number of authors have reported large seed losses within uncultivated fields without knowing the exact reason for them.[75,76] However, there is no simple relation between tillage intensity and seed predation. Studies by Cromar et al. in Ontario, Canada, for instance, showed that the seed predation of *Chenopodium album* and *Echinochloa crus-galli* was particularly high in no-till and plowed fields but was significantly lower in chisel-plowed fields.[77]

5.4 FURTHER IMPLICATIONS OF SOIL CULTIVATIONS FOR SEED DORMANCY, GERMINATION AND EMERGENCE

5.4.1 The Stimulatory Effect of Soil Cultivations

Soil cultivation influences seeds not only by transferring them vertically in soils and thereby transferring them to a new environment, as discussed in Sections 5.3.1–5.3.5. Additionally, soil cultivations can have stimulatory effects, e.g., through exposure to light during cultivation.[78] Scopel et al. constructed a light pipe to study this effect under field conditions.[79] This instrument enabled the experimenter to expose seeds to sunlight for a very short period of time without changing the other environmental factors. Seed germination was increased significantly by light exposure the more the longer seeds were exposed to sunlight. It seemed that 1/100 sec of sunlight was enough to enhance germination by around 10%.

Seed germination in response to a light flash will not always result in successful seedling emergence, since some seeds are placed too deep in the soil, resulting in fatal germination. Nevertheless, the ability to react to extremely short light exposure apparently provides a significant competitive advantage in disturbed habitats and is relatively common among weed species.

The ability of weeds to react to extremely short light exposures, as experienced during soil cultivation, inspired Hartmann and Nezadal to suggest that weed germination in response to tillage may be utilized to suppress weed infestation in commercial fields.[80] Their hypothesis was that germination is likely to be reduced when tillage operations before sowing and sowing itself are accomplished at night instead of during the day. Various field trials at many sites have shown that this method can result in reduced weed emergence. However, its efficiency varies enormously, from increasing weed populations to decreasing them or having no effect.[81–84] This may partly be the result of varying environmental conditions during soil cultivation, e.g., soil moisture conditions. Another reason may be the seasonal variation of the dormancy levels of seeds and related variations in germinability.[85,86] Figure 5.6 summarizes the effects of daytime cultivation in late summer compared to nighttime controls, as reported in experiments by Scopel et al. at Oregon State University, USA.[83] Results are shown for winter annual dicotyledones and grasses. For both groups of weeds it was obvious that, on average, daytime cultivation produced higher seedling emergence than nighttime cultivations and at low artificial illumination.

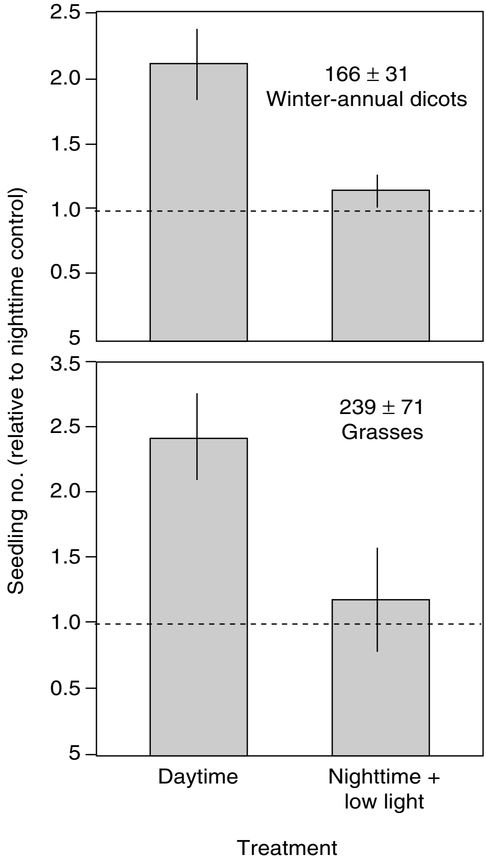

Figure 5.6 Effect of daytime cultivation in late summer on seedling emergence compared with nighttime (no light) control. Also shown is the effect of weak artificial illumination (31 μmol m^{-2} s^{-1}) during night tillage. Absolute densities after nighttime cultivations are indicated at the top of each panel in plants m^{-2} (counts made 5 weeks after the experimental cultivations). Error bars indicate 1 s.e.; n = 6 blocks. (From Scopel et al., 1994, with permission.)

Factors other than light may also play a role in stimulating the germination of seeds by cultivations. Botto et al. compared seed germination in plots that had been cultivated at night or day either using a moldboard plow or a chisel plow.[87] They found a stimulating effect of plowing during the day but not of chisel plowing during the day and concluded, therefore, that there could be factors other than light responsible for the stimulation of seed germination by tillage. These factors could be sudden changes in soil water content, temperatures, the gaseous environment, and possibly others. Also, increased mineralization as a result of enhanced aeration may be responsible for increased germination rates in response to tillage. Nitrate can alleviate seed dormancy in many species.[88] Hence, although the stimulation of germination by tillage is a well-known phenomenon, its functional relationships have not been fully resolved.

5.4.2 The Effects of Soil Structure

In traditional tillage systems, one of the most important aims of soil tillage is to create a seedbed that is optimally structured for the germination and establishment of the following crop. To achieve this, a number of cultivation operations are done, as described in the introduction of this chapter. In an ideal situation, the final results of these tillage operations are a relatively compact layer beneath the sowing horizon, which allows water to move upward towards the seeds, and a thin layer with loose and fine soil that guarantees optimal seed–soil contact, a good oxygen supply, and rapid warming of the seedbed when sowing in spring.[89,90] Hadas and Russo showed that for optimal seed–soil water contact in aggregated soils, the mean aggregate size should be very small: one fifth to one tenth of the seeds' diameter.[91] An extremely fine seedbed, however, implies an increased risk of crust formation, in particular in soils rich in silt.[92] Crusts can cause reductions in oxygen supply to the seed. Apart from that, they create a mechanical barrier for seedlings of small seeded weed species.[93,94] This is likely to aggravate seedling emergence (Figure 5.7). In addition, gaseous exchanges within the rhizosphere can be impaired by this, potentially resulting in disturbed seedling growth patterns. The most significant consequence is the warming-up effect below the crusted soil surface, described to accelerate the reproduction rate of microbial organisms, in particular pathogenic fungi but also the activity of soil invertebrates.

Crust formation is relatively unlikely in reduced-tilled soils.[95] These soils exhibit a higher bulk density and higher aggregate stability than conventionally-plowed soils. Apart from that, crop residues on the surface protect the soil against the mechanical forces of heavy rainfall. On the other hand, a relatively compact structure with large aggregates in reduced tilled soils can impair crop establishment due to

Figure 5.7 Sugar beet seedlings that had been grown beneath a crust. (Photo by El Titi).

poor soil–seed contact and large variations in sowing depth of the seed.[96] These aspects are adressed in more detail in Chapter 1.

5.4.3 The Position of Crop Residues

In no-tillage systems, all crop residues that are not removed remain on the surface. In contrast, in conventionally plowed fields, the ground is free of vegetation at the time of sowing. This difference has a decisive effect on the germination and fate of seeds, both on crop and weed seeds. In no-till soil surface, crop residues can interfere with the sowing process.[97] This is particularly likely under humid weather conditions when the straw is not properly cut by disks but builds up in front of the drills and is pressed into sowing slots (see Reference 98; also see Chapter 1). Seeds lying on the surface of the straw are suboptimally provided with water and therefore emergence success can be significantly reduced. Additionally, chemical inhibitors originating from crop residues can reduce crop establishment in no-till systems.[99,100] Poor crop establishment can also be attributed to various other reasons such as herbivorous activity, e.g., by slugs (see Chapter 8). An additional constraint for crop establishment can be increased soil water content of no-till soils compared to conventionally plowed soils. Crop residues decrease unproductive evaporation[101,102] and therefore have a water-saving effect. This is of benefit under conditions of water stress but can be a disadvantage in temperate climates for the establishment of spring-sown crops. A moister and cooler soil can retard crop establishment. However, on the other hand, crop residues minimize runoff and erosion,[103] thereby enhancing the establishment of small seeded crops, such as sugar beet or oilseed rape, that require a fine seedbed and therefore run a high risk of being washed away by eroding rainfall after sowing.

Crop residues affect not only the establishment of crops, but also possibly weeds. Buhler states that the implication of crop residues for weed seed germination appears to be very complex.[11] It is controlled by several interacting factors such as the type and quantity of residues, weed species, seed position in the soil, soil type, etc. Surface crop residues can enhance the germination and emergence of weeds as a result of increased water availability on the surface respective at shallow depths.[104] However, on the other hand, surface crop residues can act as a mechanical barrier for weed emergence. Also, allelopathic substances that originate from decaying crop residues can inhibit seed germination.[105,106] This effect can be more pronounced in no-till soils, as shown in studies by Teasdale et al.[107] or Mohler and Teasdale,[108] or it can be the opposite, as shown in studies by Petersen.[109] Table 5.9 summarizes the results of a 4-year-old experiment in Maryland, USA. Whereas in no-till plots weed densities were reduced significantly by hairy vetch or a rye cover crop, no weed-suppressing effects of cover crops were observed in plots with conventional plowing. In contrast, in experiments by Petersen, allelopathic substances originating from *Brassica oleracea* residues prevented weed seed germination only after residues had been incorporated into the soil (Table 5.10).[109] When crop residues were left on the soil surface, weed seed germination was unaffected by the cover crop.

Table 5.9 Influence of Cover Crop in No-Tillage and Conventional-Tillage Treatments

Tillage Regime	Cover Crop	Weed Density (Plants m^{-2}) 1986	1987	1988	1989
no tillage	none	27a	221b	612c	304b
	rye	19a	184bc	96b*	199c
	hairy vetch	25a	152b	166b*	88b*
conventional tillage	none	41a	54a	284b	224b
	rye	40a	57a	317b	394b
	hairy vetch	43a	73a	214b	157b

Applied to the plots in 4 consecutive years on weed emergence 1 month after planting sweet corn. Values within row followed by the same letter are not significantly different according to the LSD (0.05) test. Values within columns and tillage regime followed by an asterisk are significantly different from the treatment without cover crop according to the LSD (0.05) test.

Source: From Teasdale et al., 1991, with permission.

Table 5.10 Germination (%) of Weed Seeds

Weed Species	Without Cover Crop	Crop Residues on the Soil Surface	Crop Residues incorporated	LSD (0.05)
Amaranthus hybridus	100	97.5	124.7	22.2
Matricaria inodora	100	106.7	73.9	21.4
Sonchus asper	100	95.8	47.8	11.3
LSD (0.05)		10.9	22.4	

As affected by cover crop (*Brassica Rapa*) with and without incorporation of cover crop residues into the soil.

Source: From Petersen, 1999, with permission.

5.5 THE IMPLICATIONS OF CULTIVATION REGIMES FOR SEEDBANKS AND ESTABLISHMENT OF CROPS AND WEEDS

Sections 5.3 and 5.4 analyzed in detail single aspects of soil cultivation. Wherever possible, short-term effects of soil cultivations were considered, including data from laboratory studies or model experiments. In this chapter, the combined effect of several aspects is shown, thereby demonstrating long-term effects of tillage regimes on crop and weed seeds.

When changing from regular inversion tillage to no-tillage, weed and volunteer problems tend to increase and crop establishment can be impaired. Both factors together can result in enhanced weed growth if no adequate control measures are taken, in particular if no herbicides are applied.[110–112] The main reason for increased populations of annual weeds and volunteers is the accumulation of seeds within the upper soil layers.[113–116] Apart from annual weeds, perennial weeds benefit very much from reduced tillage. However, these are not considered in this chapter. (See Chapter 6).

On the one hand, the accumulation of seeds within the upper soil layer should result in a faster decline of the seedbank. Seeds on or close to the soil surface are exposed to dormancy-terminating factors such as light, alternating temperatures, a drying soil surface, etc. at higher intensity than seeds that are buried deep in the profile.[117,118] Moreover, the probability of seed predation should be greater for seeds lying on the surface compared to seeds buried in the soil. On the other hand, reduced tillage or no-tillage systems imply less direct stimulation of weed seeds by tillage.[117,119–121] More importantly, as a result of the shallow position of weed seeds in reduced-tilled soils the probability of successful seedling emergence is significantly higher than in conventionally-plowed soils. This results in increased weed seedling populations and, as a result, in increased weed seed production and, in the long run, in population increases if weed populations are not adequately controlled. An accumulation of seeds within the upper soil horizon and the related increases in weed problems can also be the result of reduced plowing depths,[122] which for other reasons is seen as a positive option in organic farming.[123]

Whether or not weed and volunteer plant problems increase depends on a number of factors. These include crop rotations, climatic and soil conditions, the prevailing weed species,[124] and the efficacy of available control measures. The reliability of any conclusions drawn on effects on soil seedbanks of tillage requires long-term on-farm examination. Such an approach should match available technologies, e.g., which crops to consider, commercially available farm machinery, available herbicides, etc. A number of such long-term experiments targeting the exploration of integrated farming systems are being conducted in Europe and elsewhere.[125,126] Only a few of these comprehensive farming system studies have explored the effects of farming systems on soil seedbanks. Studies at Lautenbach in Germany aiming at contrasting an integrated farming system (IFS) against a conventional farming system (CFS) have been cited in Chapter 2 already. Figure 5.8 illustrates seedbanks in the rootable soil profiles of both systems after 17 years. The results indicate clearly that weed seed densities are closely related to the site and its agronomical history. The seedbanks assessed for the IFS in fields I and V were significantly higher than those for the CFS. Results from field IV show the opposite. Weed seeds in the CFS soils were more abundant than in the adjacent IFS soils. This applies to the total density of weed seeds over the soil profile to a 30-cm depth. The soils of the IFS contained more weed seeds than those of the CFS, but these were accumulated in the top 10 cm (>75%). The distribution pattern in IFS noninversion-tilled soils is supported by the results presented in Figure 5.3. However, with regard to the exceptional case of field IV the higher weed seed density in the CFS-plowed soils do not really reflect the average weed density in the crops grown over the previous 16 years. Hence, the weed infestation incidence in the crops was regularly greater under IFS than CFS. The higher survival rates of some weed species, in particular *Lamium purpureum* and *Polygonum convolvulus*, could be attributed to specific weakness of the applied herbicides and had apparently contributed to restoring soil seedbanks of the CFS. In addition, the alternation of crop sequences may have had an additional impact of weed seed input to the CFS soil.

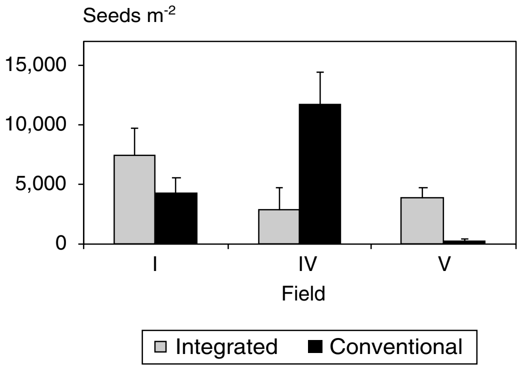

Figure 5.8 Weed seedbank (seeds m^{-2} in 0–30 cm) in an experiment at Lautenbach in southwest Germany where integrated and conventional farming had been compared for 17 years. Results are shown for three fields. Integrated farming consisted of noninversion tillage at around 25 cm depth and a package of agronomical means according to principles of integrated farming; conventional farming consisted of annual plowing at 30 cm depth and agronomical input, as recommended by extension services. Error bars = 1 standard deviation.

Seed population increases as a result of reduced tillage are particularly relevant for plant species with short-lived seeds as well as for crop seeds and the majority of annual grasses.[127] In systems using regular plowing, these seeds have a relatively small chance to emerge and reproduce successfully since during their life span many seeds have no chance to emerge and reproduce successfully. In contrast, species with long-lived seeds are not so much affected by cultivation regime as their seeds remain ungerminated as long as conditions are unfavorable for emergence. Hence, these species conserve seeds for situations with good conditions for establishment and seed production in the future.

There are also situations where no-tillage is the best option to prevent weed problems. To avoid any long-term persistence of oilseed rape seeds, for instance, shed seeds should be left on the stubble for as long as possible after harvest.[48,128] Incorporating oilseed rape seeds into dry soil in summer is related to the significant risk that the seeds will develop secondary dormancy and persist in soil until subsequent years (Table 5.11). Plowing the stubble after simulated seed losses of around 10,000 seeds m^{-2} resulted in extremely large numbers of persisting seeds. Repeated stubble tillage decreased seedbanks. Lowest persistence rates, however, were observed in no-tillage plots, where seeds remained on the soil surface before the sowing of winter wheat. Similar observations have been made in relation to sunflower seeds.[129] Broadcasting freshly harvested sunflower seeds on the stubble to simulate harvesting losses resulted in the development of a seedbank when the seeds were incorporated into the soil soon after the start of the experiment. No seedbank, or a very small seedbank, remained where no-tillage was used. Hence, although there is a tendency for increased weed problems in reduced-tillage systems, there are also situations where no-tillage can be an option to minimize weed problems.

Table 5.11 Seedbank (ln of % Seeds in 0–30 cm) of Oilseed Rape in Spring 1996 at Rothamsted and Woburn as a Function of Soil Cultivation the Previous Summer

Cultivar	Plough	3* Tine	Delay Plough	Delay Tine	Zero Tillage
			Rothamsted		
Apex	2.351	2.314	1.251	–0.002	–0.693
	(12.7)	(12.5)	(3.2)	(0.8)	(0)
Bristol	2.695	2.144	1.231	0.629	–0.500
	(14.8)	(9.9)	(3.4)	(1.5)	(0.2)
Envol	2.124	1.949	0.308	–0.485	–0.693
	(8.6)	(7.0)	(1.1)	(0.2)	(0)
standard error of means 0.2715, d.f. = 38* (same level of cultivation 0.2532) (d.f. 30)					
			Woburn		
Apex	3.378	2.937	1.270	0.109	–0.693
	(38.2)	(25.5)	(3.7)	(0.7)	(0)
Bristol	3.443	3.024	1.721	–0.392	–0.693
	(43.4)	(23.4)	(5.1)	(0.3)	(0)
Envol	3.836	3.000	1.237	–0.485	–0.278
	(62.7)	(20.6)	(3.2)	(0.2)	(0.3)
standard error of means 0.3203, d.f. = 33* (same level of cultivation 0.2740) (d.f. 30)					

*degrees of freedom estimated using the Satterthwaite's formula (see Payne et al., 1995).

Seeds were broadcast at a rate of around 10,000 seeds m^{-2} in July–August 1995 to simulate harvesting losses. Consecutively, tillage was carried out as follows: plow = immediate plowing; 3* tine = 3* repeated stubble tillage using tine before plowing; delay plow = 4 weeks no cultivation, then plow; delay tine = 4 weeks no tillage, then noninversion tillage; zero tillage = no tillage. Mean of 4 replicates. Means of original values in parentheses.

Source: From Pekrun et al., 1998, with permission.

5.6 CONCLUSIONS ON IMPLICATIONS OF WEED SEEDS FOR SUSTAINABLE CROP PRODUCTION

Soil cultivations have been carried out probably for as long as humans have grown crops, mainly to generate an optimal seedbed and remove old vegetation, so as to maximize seedling establishment and early growth of crop. Modern farming, however, has changed two aspects of the situation completely. Herbicides can fully replace the weed-controlling effect of tillage. Modern sowing machines can place seeds into uncultivated and firm soil and therefore guarantee adequate crop establishment without any prior tillage. However, neither technology is available in every situation. In many areas of the world, herbicides and specific sowing machines for zero-tillage seeding are not available for economic reasons. In organic farming, herbicides are not available for reasons of principle. Moreover, noninversion tillage, and in particular no-tillage, is not feasible on every soil and under all climatic conditions. Hence, the implication of tillage for sustainable crop production must be seen in the context of a specific farming system. Under the conditions of a temperate climate with moderate rainfall, the following differentiations need to be

considered in conventional, integrated, and organic farming systems. The guiding principle must be the adaptation of tillage type, intensity, and machinery to support the crops, suppress competitors, and minimize the unavoidable anthropogenic impact on the interrelationships between organisms and their soil environment.

In CFSs, an extreme reduction of tillage is possible in principle and should be used wherever possible. Reduced tillage provides ecological and economic advantages such as reduced erosion, lower costs for labor, fuel, and machinery, etc. However, when changing to noninversion tillage or no-tillage, herbicide programs need to be adapted to the specific situation. This very often will imply the additional application of a nonselective herbicide prior to sowing to clear the ground of weeds and volunteer plants. Additionaly, weed-control options need to take into account an increased occurrence of annual grasses and perennial weeds. These adaptations in weed control are usually very manageable. At sites where continuous noninversion tillage is not feasible, the time and intensity of tillage should be adjusted to avoid any negative effects of tillage on the environment, by growing cover crops between two main crops to avoid erosion and nutrient leaching, by carrying out tillage at adequate soil water conditions to avoid compaction, by adjusting time and intensity of tillage to minimize nutrient losses via leaching or gaseous emissions, and by applying indirect weed control to contain weed populations, in addition to using herbicides.

In IFSs, a conflict of interests must be managed. According to the IOBC definition, integrated production "is a farming system that produces high-quality food and other products by using natural resources and regulating mechanisms to replace polluting inputs and to secure sustainable farming."[130] Under these conditions, the aim of soil conservation is to maintain and manage natural resources, e.g., soil nutrient reservoirs, antagonistic agents of noxious species on grown crops, etc. These resources and natural regulating components will establish the ground to replace off-farm inputs, e.g., pesticides. This does not signify a competition with the objective of pesticide reduction but rather a supporting project. The success of this strategy has been proven repeatedly.[126,131–133] Minimal soil tillage in IFSs has revealed significant increases in soil humus content[133] in higher soil carbon storage with both agricultural and environmental functions (C-sequestration and air quality),[134] and a higher species diversity.[132] However, despite the feasibility of an IFS strategy, site traits, the potential crops, and farmers' perceptions of their guiding idea must be considered. Eventual discrepancy between targets and achievements, in particular in the transition years, should be considered on a case-by-case basis, always giving priority to the preservation of natural resources and regulating mechanisms. An arable soil, in particular an arable soil of high fertility, is an important slowly-regenerating resource; this means that in many cases reduced tillage must be used to avoid soil losses. Higher weed infestations can be resolved partially by adjusting rotations and improving weed-control efficiency. Other main principles of weed management that have been discussed under the former heading "conventional systems" as adjustment of tillage in time, machinery, and intensity have the same validity under an IFS.

In organic farming systems, the situation is completely different since no herbicides are allowed. Hence, all methods to control weeds are of enormous importance. Tillage, and in particular plowing, is one of the most effective means to suppress weeds, not

only annual but perennial weeds as well. Shallow plowing combined with deep soil loosening can be seen as a good solution in organic farming since it combines both mechanical weed control by plowing with soil conservation as far as possible. Specific types of plows have been constructed to achieve this effect. However, not many experiments have been done to test the implication of this system for crop and weed growth and so cannot be evaluated fully at the moment. As mentioned for the previous two systems, tillage should be used in an adapted way to avoid negative impacts on the environment and to keep plant nutrients within the system.

These three examples demonstrate that the implications of tillage for sustainable crop production are very diverse and can be judged only in the context of whole farming systems. Conclusions that have been drawn from one particular production system need not be valid under another one. This is also true when considering farming systems under a range of climatic and soil conditions. At the same time, however, it should be remembered that tillage of large areas of land is a man-made philosophy. In natural ecosystems, soil disturbance is limited, with regard to both space and frequency of disturbance. To avoid negative impacts of tillage soil disturbance should be applied only as often and as intensively as necessary to ensure adequate crop growth and to contain weed populations at an acceptable level.

5.7 SUMMARY

Tillage has a great impact on seeds—both crop and weed seeds. It affects the vertical distribution of seeds within the soil and hence environmental conditions—light environment, temperature regime, soil water conditions, the gaseous environment, and the probability of seeds being removed by animals. Additionally, it affects seeds by its stimulatory effect and indirectly via its impacts on soil structure and placement of crop residues. All these factors together influence seed dormancy, germination, the probability of emergence, and, as a result, the establishment of the crop as well as population dynamics of weeds and volunteers.

Generally, a position deep in the soil profile enhances the survival of seeds, whereas shallow positions increase germination. Nevertheless, minimal tillage tends to increase overall weed infestations. Consequently, although reduced tillage aims at minimizing the disturbance of soil ecosystems, skilled management and understanding of seed germination patterns are indispensable prerequisites for adopting such ecosystem-based approaches. The needed managerial skills should match the site, crop rotation, and concerned seed species and sustain cost-efficiency, farm income, and environmental safety.

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